Optical-Microwave Sensor for Real-Time Measurement of Water Contamination in Oil Derivatives

Russul Khalid Abdulsattar, Mohammad Alibakhshikenari, Bal S. Virdee, Richa Sharma, Taha
A. Elwi, Lida Kouhalvandi, Zaid A. Abdul Hassain, Syed Mansoor Ali, Nurhan Türker Tokan,
Patrizia Livreri, Francisco Falcone, and Ernesto Limiti

***Abstract*— This paper presents a novel microwave sensor using optical activation for measuring in real-time the water contamination in crude oil or its derivatives. The sensor is constructed from an end-coupled microstrip resonator that is interconnected to two pairs of identical fractal structures based on Moore curves. Electromagnetic (EM) interaction between the fractal curves is mitigated using a T-shaped microstrip-stub to enhance the performance of the sensor. The gap in one pair of fractal curves is loaded with light dependent resistors (LDR) and the other pair with microwave chip capacitors. The chip capacitors were used to increase the EM coupling between the fractal gaps to realize a high Q-factor resonator that determines the sensitivity of the sensor. Empirical results presented here show that the insertion-loss of the sensor is affected by the change in LDR impedance when illuminated by light. This property is used to determine the amount of water contaminated oil. The sensitivity of the sensor was optimized using commercial 3D EM solver. The measurements were made by placing a 30 mm diameter petri dish holding the sample on top of the sensor. The petri dish was filled up to a height of 10 mm with the sample of water contaminated crude oil, and the measurements were done in the range between 0.76 GHz to 1.2 GHz. The Q-factor of the oil sample with no water contamination was 70 and the Q-factor declined to 20 for 100% contamination. The error in the measurements was less than 0.024%. The sensor has dimensions of $0.127\lambda_0 \times 0.127\lambda_0 \times 0.004\lambda_0$ and represents a new modality. Compared to existing techniques, the proposed sensor is simple to use, readily portable and is more sensitive.**

***Index Terms*— Microstrip sensor, electromagnetic (EM) spectrum, fractal curves, light dependent resistors (LDR).**

I. INTRODUCTION

EVALUATING the quantity of dissolved water in crude oil or its derivatives is important since purchase, sale and transfer of this commodity are based on net dry oil. In maintaining the operation of refineries, low water content is critical [1]-[2]. Determining the water content in the oil is also crucial for the quality control of the products such as lubricating oils. Water in lubricating oil results in premature aging of the oil which may harm machinery by accelerating the oxidization. Therefore, a sensor is required that can continuously monitor water dissolved in oil.

Currently there are numerous methods to determine the amount of water in crude oil [3]-[8]. In the Dean & Stark method, a solvent is added to the oil sample and then heated under reflux conditions. This process co-distills water and solvent. A measuring tank is used to collect the resulting condensate where the water droplets sink to the bottom of the tank and are measured against the scales. A heated centrifuge

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R.K. Abdulsattar is with the Medical Instrumentation Technical Engineering Department, Al-Hadi University College, Baghdad, Iraq (e-mail: rusul.khalid@huc.edu.iq).

M. Alibakhshikenari is with the Department of Signal Theory and Communications, Universidad Carlos III de, Madrid, Spain; (e-mail: mohammad.alibakhshikenari@uc3m.es).

B.S. Virdee and R. Sharma are with the School of Computing and Digital Media, Center for Communications Technology, London Metropolitan University, U.K. (e-mail: b.virdee@londonmet.ac.uk & r.sharma@londonmet.ac.uk).

T.A. Elwi is with the International Applied and Theoretical Research Centre (IATRC), Baghdad, Iraq (e-mail: tahaelwi82@almamonuc.edu.iq).

L. Kouhalvandi is with the Department of Electrical and Electronics Engineering, Dogus University, Istanbul 34775, Turkey (e-mail: lida.kouhalvandi@ieee.org).

Z.A. Hassain is with the Electrical Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq (e-mail: zaidasaad_79@yahoo.com).

S.M. Ali is with the Department of Physics and Astronomy, College of Science, P.O. BOX 2455, King Saud University, Riyadh 11451, Saudi Arabia (e-mail: symali@ksu.edu.sa).

N. Türker Tokan is with the Department of Electronics and Communications Engineering, Yildiz Technical University, Esenler, Istanbul 34220, Turkey (e-mail: nturker@yildiz.edu.tr).

P. Livreri is with the Department of Engineering, University of Palermo, viale delle Scienze BLDG 9, Palermo, IT 90128, Sicily, Italy (e-mail: patrizia.livreri@unipa.it).

F. Falcone is with the Electric, Electronic and Communication Engineering Depart., and Institute of Smart Cities, Public University of Navarre, Spain. He is also with the Tecnologico de Monterrey, School of Engineering and Sciences, Monterrey 64849, Mexico (e-mail: francisco.falcone@unavarra.es).

E. Limiti is with Electronic Engineering Depart., University of Rome “Tor Vergata”, via del Politecnico 1, 00133 RM, Rome, Italy (e-mail: limiti@ing.uniroma2.it).

can also be used to separate the water from the oil. Other methods for determining the amount of water in crude oil include microextraction and capillary gas chromatography, Karl Fischer titration, solvent extraction using Mid-IR laser spectroscopy, accelerated solvent extraction using gas chromatograph with flame ionization detector, liquid-liquid extraction, and high-performance liquid chromatography with coupled ultraviolet and fluorescence detection. Although these methods are highly accurate however they are time-consuming and require expensive equipment that is not portable. Moreover, these conventional methods cannot monitor contamination in real-time.

Microstrip resonators have recently become popular for sensor application in chemical and biomedical fields [9]-[11]. Compared to the conventional sensors described above, microstrip sensors lack the level of sensitivity needed to accurately detect small amounts of contamination. The metric used to quantify the sensitivity of such sensors is based on the variations of the resonant frequency (f_o), transmission coefficient (S_{21}), and the quality (Q) factor. Various approaches have been investigated to increase the sensitivity of such sensors, including fabricating the sensors on low loss dielectric substrates [12], employing different resonator structures [13],[14], and incorporating metamaterial technology [15]-[17].

In this paper, a novel microwave sensor is proposed based on optical illumination for real-time measurement of water contamination in a sample of crude oil. The sensor is a microstrip resonator that is based on Moore's fractal curve [11]-[12]. The sensor is loaded with light dependent resistors (LDR). By illuminating the petri dish with the sample of the crude oil, which is placed on top of the sensor, the impedance of the LDR will be determined by the amount of light penetrating through the sample. This will affect the Q-factor of the sensor [18]. The measured Q-factor is used to accurately determine the amount of contamination. Compared to other microwave sensors reported recently in literature the proposed sensor has the highest Q-factor of 70 with no contamination [12],[15],[19]-[22]. The error in the measurements made between 0.76 GHz and 1.2 GHz was less than 0.024%. The sensor has dimensions of $0.127\lambda_o \times 0.127\lambda_o \times 0.004\ \lambda_o$. The proposed method is simple to use, inexpensive and fast compared to existing techniques such as microextraction, capillary gas chromatography, solvent extraction using Mid-IR laser spectroscopy.

II. PROPOSED MICROSTRIP SENSOR

The principle of the proposed LDR loaded sensor is illustrated in Fig.1. The sample of the contaminated oil is placed over the sensor which will restrict the illumination of the LDR. The impedance of the LDR is affected by the intensity of the light falling on it. This will perturb the characteristics of the sensor in terms of its insertion-loss and Q-factor. The RF output from the sensor is converted to a DC voltage using an RF power detector. The amount of light penetrating the sample over the sensor will affect the magnitude of the DC voltage. By carefully calibrating the output voltage of the sensor, the exact amount of contamination can be determined. With this technique the contamination can be measured in real-time without resorting to expensive equipment.

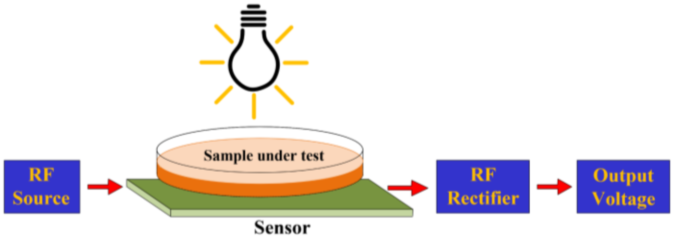


Fig. 1. Simplified block diagram of the proposed LDR based microwave sensor.

The geometry of the proposed sensor, which is shown in Fig.2, is based on a single pole end-coupled microstrip resonator. The coupling gaps are bridged with high impedance transmission lines which are configured into a 4th order Moore fractal curve. A fractal is a continuous space-filling curve and in the present case, it is a variant of the Hilbert curve. The dimensions of the fractal were calculated at the resonance frequency of the sensor. The number of segments required in the fractal of order n was determined using [23]

$$N_n = nN_1 \qquad (1)$$

where N_1 refers to the number of fractal segments of Moore curve for a single copy. The total length of the fractal, L^n was calculated using:

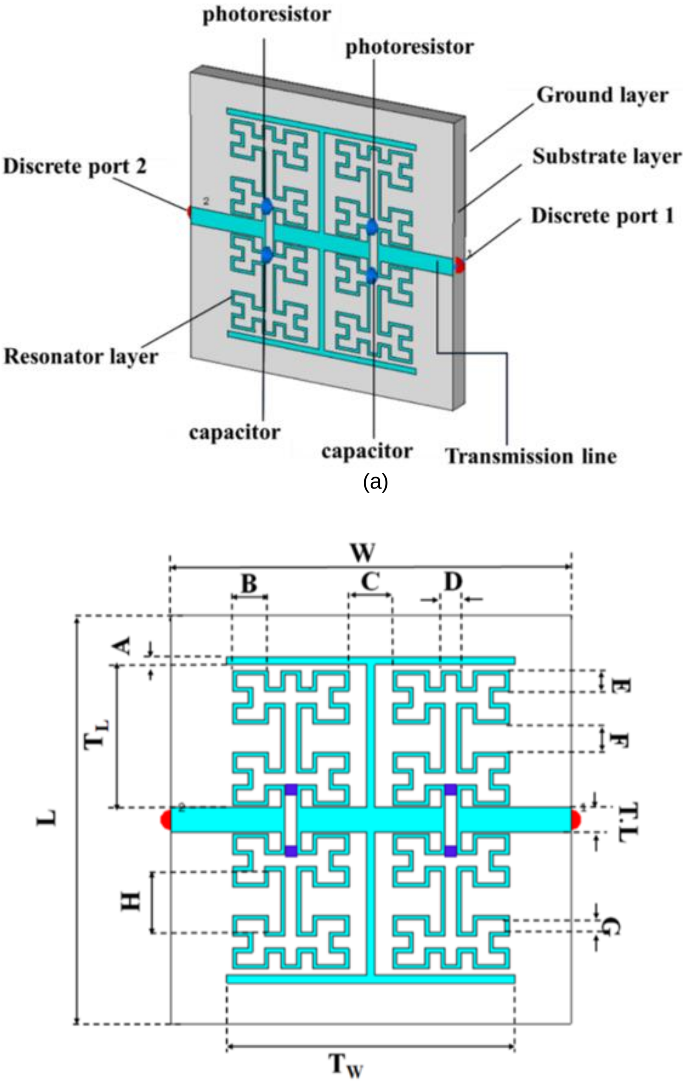
$$L^n = \frac{8n}{2n+3} L_0^n \qquad (2)$$

where L_0^n is the perimeter of rectangle that occupies the same area as the fractal curve.

The coupling gaps of the resonator are loaded with a pair of fractal curves in a parallel formation. The fractal gap of the upper set of fractal curves near the transmission line is loaded with light dependent resistor, and the fractal gap of the lower set of fractal curves is loaded with microwave chip capacitors. The chip capacitance was inserted to increase the EM coupling between the fractal gaps. Electromagnetic interaction between the adjacent fractal curves due to surface waves is suppressed with T-shaped stub connected to the center resonator. This has an effect of enhancing the sensitivity of the sensor. The full-wave electromagnetic solver based on finite integration technique (FIT) by CST Microwave Studio was used to optimize the sensor at 0.76 GHz. The sensor was fabricated on standard FR4 substrate with a ground plane. Effects of transmission line width and substrate thickness on S-parameters were investigated in [11]. Each of the fractal curves in Fig. 2 occupies a surface area of $16.5 \times 14.5\ \text{mm}^2$.

A. Effect of LDR Loading on the Sensor

The impedance of the LDR is dependent on the intensity of the photons (light) impinging on it. When LDR is fully illuminated with light it has an impedance value of 1 Ω, which can be considered as a virtual short circuit. However, when it is fully deprived of light its impedance increases to 1 MΩ. In the sensor, LDR is used to detect the variation through controlling the resistive part of the fractal section with respect to the sample under test. Fig.3(a) shows how the insertion-loss of the sensor (S_{21}) varies under two extreme cases, i.e., when LDR is fully illuminated with light and vice versa. It is evident that when the LDR is fully exposed to light the notch frequency shifts from 0.76 GHz to 1.2 GHz. This demonstrates that LDR can be used at microwave frequencies.

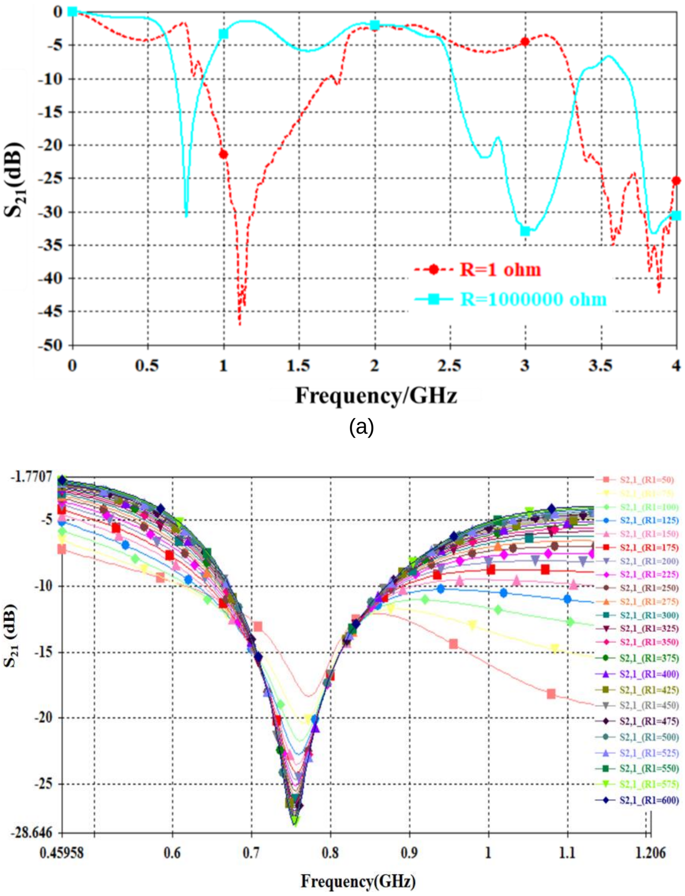


(a)

(b)

Fig. 2. Geometry of the proposed sensor: (a) isometric view, and (b) front view. Dimensions are L = W = 50 mm, T_L = 18 mm, T_w = 36 mm, A = 1 mm, B = 4.5 mm, C = 5.5 mm, D = E = 2.5 mm, F = 3.5 mm, G = 1.5 mm, H = 8.5 mm, and T.L = 2.79 mm.

In practical application, LDR in the sensor will not be fully illuminated with the light as it will be covered with the crude oil sample. It is observed from the simulated results that the impedance of LDR varies between 50 Ω and 600 Ω. The effect on the sensor's insertion-loss spectra over this impedance range is shown in Fig.3(b). It can be discerned from the S_{21} variation that as the resistance of LDR decreases gradually from 600 Ω to 50 Ω, the insertion-loss at the notch frequency of 0.76 GHz decreases from approximately -27 dB to -18 dB with negligible change in the notch frequency. However, the out of band insertion-loss deteriorates significantly for resistance values less than 200 Ω. These results show that when the proposed sensor with LDR is properly calibrated, it can be used to measure the amount of water content precisely.



(a)

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Fig. 3. (a) S_{21} variation of the sensor loaded with LDR when LDR is illuminated (R = 1 Ω) and not illuminated (R = 1 MΩ), and (b) S_{21} variation of various LDR resistances analogous to exposure to different amounts of light.

B. Effect of Capacitive Loading on the Sensor

The effect of the chip capacitor loading on the sensor's insertion-loss response is shown in Fig.4 when the LDR is totally deprived of light. By comparing the insertion-loss of the sensor under the same lighting conditions in Fig.3, it is evident that by loading the sensor with capacitance, the Q-factor of the resonance at 0.76 GHz increases. The loss too increases from -28 dB to -37 dB. It is also evident that capacitive loading of 0.4 pF to 1.2 pF has negligible effect on the sensor's resonance frequency. The higher capacitance increases the loss but reduces its Q-factor marginally. The out of band insertion-loss, however, is greatly affected by the lower capacitance value. As the sensor operation will be confined over the region of its resonance frequency, the out of band response is not of concern and can be effectively ignored.

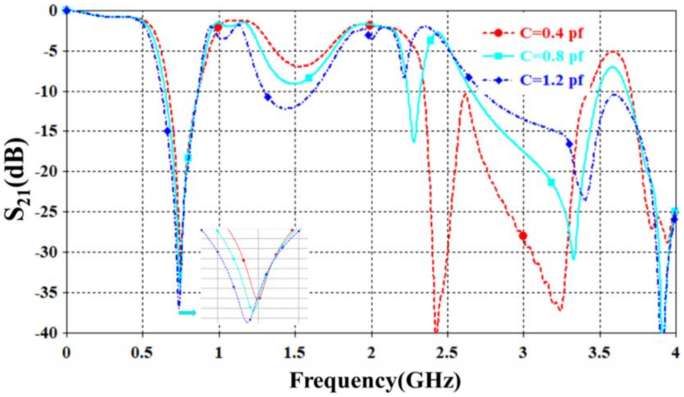


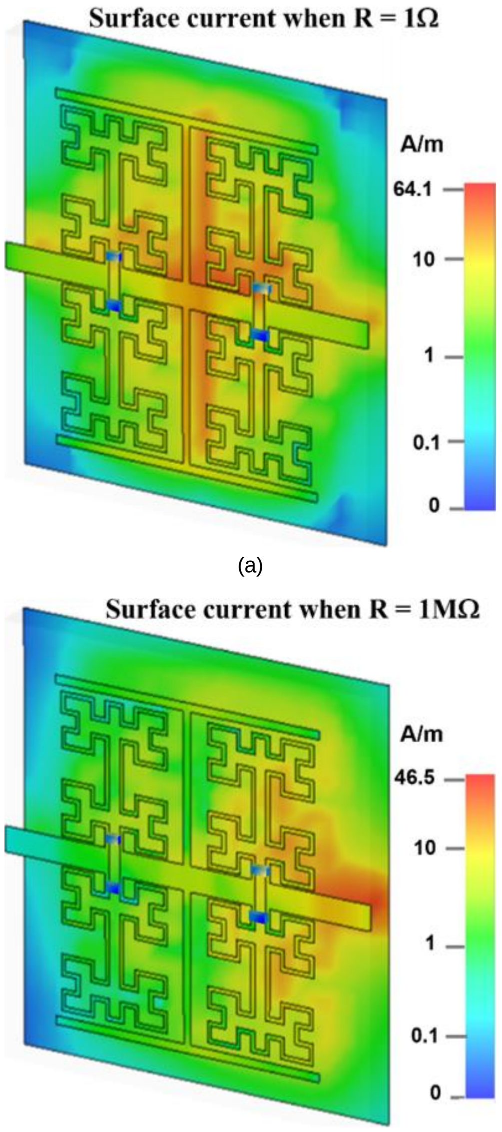
Fig. 4. S_{21} variation of the sensor for different chip capacitor loadings when LDR is illuminated with a light source.

III. RESULTS, DISCUSSIONS, AND VALIDATION

Fig.5 shows the surface current density distribution over the sensor at 0.76 GHz under two extreme conditions of being fully illuminated with light (1 Ω) and when it is not exposed to any light (1 MΩ). This is attempted as an experimental validation to ensure the effects of the photoresistors on the current motion along the Moore traces as well as to determine their effects on the frequency resonance. The red shading in the color spectrum chart indicates the regions over the sensor where there is the greatest concentration of surface currents. When the sensor is fully illuminated with light, the lateral region at the center of the sensor is where surface currents appear to concentrate.

The fabricated sensor is shown in Fig.6(a). A petri dish was placed over the sensor. The insertion-loss (S_{21}) response variation of the sensor was measured as the function of frequency under two extreme lighting conditions. In the first scenario, the petri dish was filled with water and the sensor was fully illuminated with light of 800 lumens from a regular incandescent 60W bulb. The measured results in Fig.6(b) show the sensor resonated at 1.2 GHz. However, when the petri dish was filled with black crude oil, the sensor was totally deprived of light. Under this condition the sensor's resonant frequency dropped to 0.76 GHz. The measured results show remarkable agreement with the simulation results given in Fig.3(a) for LDR resistance values for fully illuminated (R = 1 Ω) and completely deprived of light (R = 1 MΩ).

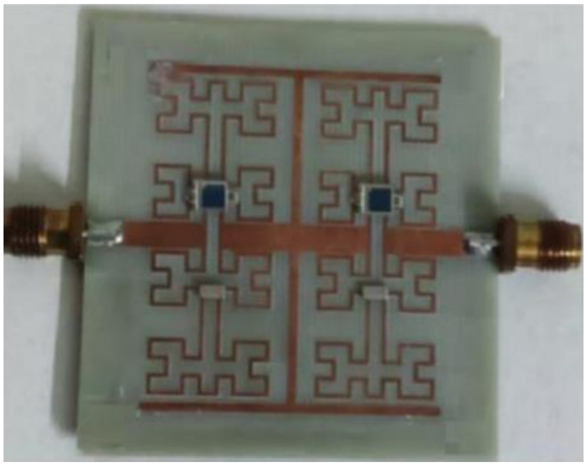
Fig.7(a) shows the experimental setup for the proposed sensor. The output of the sensor was connected to a monolithic logarithmic RF power detector (LT®5538) that converts the RF signal from 40 MHz to 3800 MHz to a DC voltage. This device is capable of measuring RF signals over a wide dynamic range, from –75 dBm to 10 dBm. The output voltage depends on the degree of light illuminating the sensor. For calibration purpose the petri dish over the sensor was first filled with water and the output dc voltage was measured. As the volume of the sample will affect the measurements in the study the petri dish of diameter 30 mm was then filled with the sample up to a height of 10 mm. The petri dish holding the sample was placed on top of the sensor and its voltage was measured with crude oil with various percentages of water contamination. The measurements were done at a room temperature of 23ºC.



(a)

(b)

Fig. 5. Simulated surface current density distribution at 0.76 GHz over the sensor for LDR impedance of (a) 1 Ω (fully illuminated with light), and (b) 1 MΩ (fully blocked from light).



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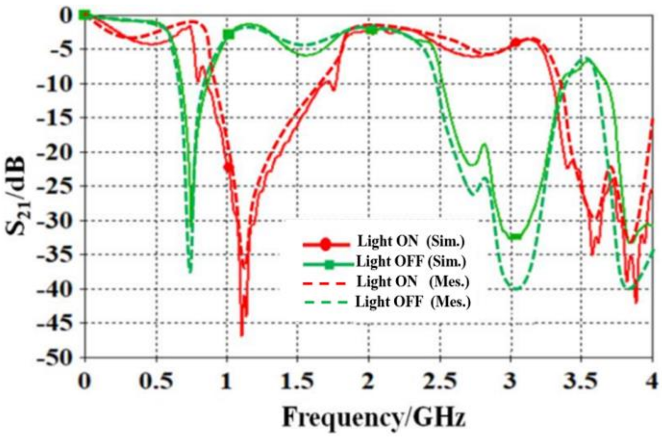
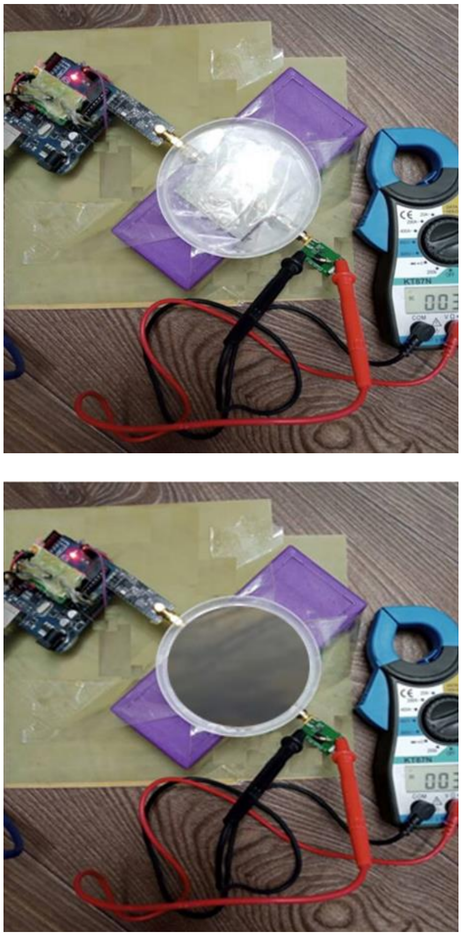


(b)

Fig. 6. Experimental validation (a) Front view of the fabricated sensor, and (b) S_{21} variation of the sensor as the function frequency in light 'on' and 'off' conditions. Under light 'on' condition the sensor was illuminated with 800 lumens from a 60W incandescent bulb.

Fig.7(b) shows the variation of the insertion-loss (S_{21}) is due to the change in the dielectric coefficient of the crude oil contaminated with water. S_{21} was measured at the sensor's resonant frequency in the range between 0.76 GHz and 1.2 GHz. With 0% contamination, the magnitude of the insertion-loss measured is -35 dB, and with 100% contamination the loss is -5.8 dB. Curve fitting equation describing the variation is annotated on the graph. The Q-factor as function of the water content is shown in Fig.7(c). The Q-factor declines approximately inversely with increasing water content from a value of 72 to 20. The output voltage from the sensor for different levels of water contamination is shown in Fig.7(d). For no contamination the measured output voltage is 18 μV and when fully contaminated it drops to 4.85 μV. The measurement error was less than 0.024%. The calibrated graph in Fig.7(d) was used to measure the exact amount of water contaminating crude oil.

Table 1 shows the performance comparison between the proposed sensor and other recently published microwave sensors. Although the sensors listed in the table are developed for analyzing different organic samples the novelty of the proposed sensor is the use of a resonator based on fractal curves that uses photoresistors to determine water contamination in oil derivatives. Compared to other microwave sensors cited in the table the proposed sensor offers the highest Q-factor of 70 with no contamination. The proposed sensor is simple to design, compact and is a cost-effective solution.



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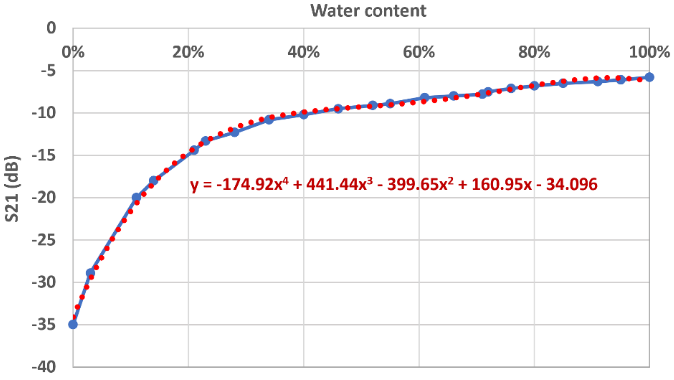

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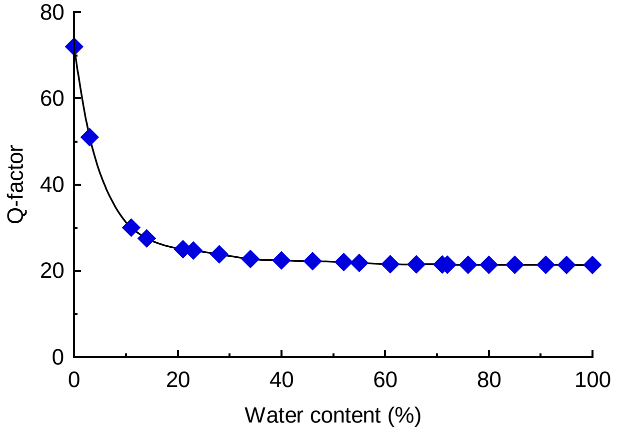

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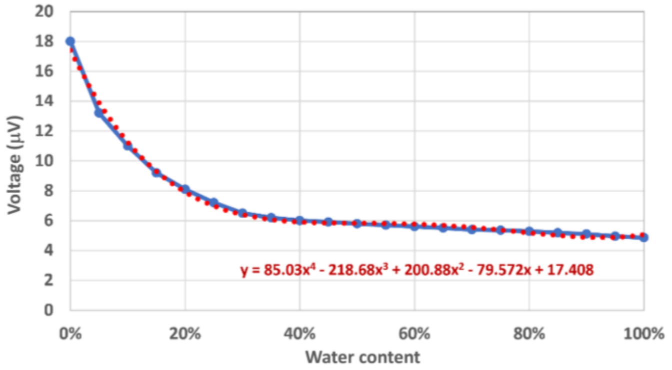

(d)

Fig. 7 (a) Experimental setup, (b) magnitude of S_{21} variation in dB as the function of water concentration ratio, (c) Q-factor as a function of water content, and (d) sensor's DC output voltage (V_{out}) as a function of percentage of water content. The variation in S_{21} and V_{out} is represented by the curve fit equations.

TABLE I

COMPARISON OF THE PROPOSED SENSOR WITH OTHER PUBLISHED MICROWAVE SENSORS

Ref.	***f*₀ (GHz)**	**Type of sensor**	**Area $(\lambda_o)^2$**	**Sample under test**	**Q-factor range**	**Meas. error (%)**
[12]	0.8	Moore fractal structure	0.127×0.127	Water content in crude oil	60-7.1	0.17
[15]	2.4	Circular CSRR	0.28×0.2	Water–Ethanol Mixtures	44-37	NP
[19]	4.94	Double split ring resonator	0.82×0.49	Glucose in Aqueous Sol. and Bulk Liquid	19-NP	NP
[20]	1.19	Split ring resonator	0.11×0.1	Methanol/ Acetone in Water	62-NP	0.03
[21]	3-6	0th order resonator	0.125×0.125	Water in methanol, ethanol, acetone	21-NP	9.3
[22]	2	Dual split ring resonator	0.267×0.2	Ferrous wear particles	45-NP	NP
This work	0.76-1.2	Optical-microwave Moore fractal structure	0.127×0.127	Water content in crude oil	72-20	0.024

*NP – Not provided

IV. CONCLUSION

The experimental results show the effectiveness of the proposed microwave-optical sensor for accurately measuring in real-time the amount of dissolved water in crude oil. The sensor is based on a high Q-factor microstrip resonator based on 4th order of Moore's fractal curve. Loaded on the sensor is a pair of light dependent resistors that affect the sensor's insertion-loss performance when partially or fully deprived of light. The sensor's RF output signal is converted to DC voltage. The sensor was calibrated with crude oil sample which was contaminated with different percentages of water. The proposed highly sensitive calibrated sensor can be used to measure in real-time the degree of water contamination. Compared to existing methods used in industry the sensor is relatively small, portable, highly accurate and much faster. Based on similar calibration principles the sensor can be adapted to measure contamination in other fluids.

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Mohammad Alibakhshikenari was born in Mazandaran, Iran, in February 1988. He received the Ph.D. degree (Hons.) with European Label in electronics engineering from the University of Rome ‘‘Tor Vergata’’, Italy, in February 2020. He was a Ph.D. Visiting Researcher at the Chalmers University of Technology, Sweden, in 2018. His training during the Ph.D. included a research stage in the Swedish company Gap Waves AB. He is currently with the Department of Signal Theory and Communications, Universidad Carlos III de Madrid (uc3m), Spain, as the Principal Investigator of the CONEX (CONnecting EXcellence)-Plus Talent Training Program and Marie Skłodowska-Curie Actions. He was also a Lecturer of the electromagnetic fields and electromagnetic laboratory with the Department of Signal Theory and Communications for academic year 2021–2022 and he received the “Teaching Excellent Acknowledgement” Certificate for the course of electromagnetic fields from Vice-Rector of studies of uc3m. In 2022-2023 he is spending industrial and academic research visitings in SARAS Technology Ltd Company, located in Leeds, England; Edinburgh Napier University, Edinburgh, Scotland; and University of Bradford, Bradford, England which are defined by CONEX-Plus Talent Training Program and Marie Skłodowska-Curie Actions as his secondment research visit plans. His research interests include electromagnetic systems, antennas and wave-propagations, metamaterials and metasurfaces, synthetic aperture radars (SAR), 5G and beyond wireless communications, multiple input multiple output (MIMO) systems, RFID tag antennas, substrate integrated waveguides (SIWs), impedance matching circuits, microwave components, millimeter-waves and terahertz integrated circuits, gap waveguide technology, beamforming matrix, and reconfigurable intelligent surfaces (RIS), which led to achieve more than 4000 citations and H-index above 40 reported by Scopus, Google Scholar, and ResearchGate. He was a recipient of the three years research grant funded by Universidad Carlos III de Madrid and the European Union’s Horizon 2020 Research and Innovation Program under the Marie Skłodowska-Curie Grant started in July 2021, the two years research grant funded by the University of Rome ‘‘Tor Vergata’’ started in November 2019, the three years Ph.D. Scholarship funded by the University of Rome ‘‘Tor Vergata’’ started in November 2016, and the two Young Engineer Awards of the 47th and 48th European Microwave Conference were held in Nuremberg, Germany, in 2017, and in Madrid, Spain, in 2018, respectively. His research article entitled ‘‘High-Gain Metasurface in Polyimide On-Chip Antenna Based on CRLH-TL for Sub Terahertz Integrated Circuits’’ published in Scientific Reports was awarded as the Best Month Paper at the University of Bradford, U.K., in April 2020. He is serving as an Associate Editor for (i) *Radio Science*, and (ii) *IET Journal of Engineering*. He also acts as a referee in several highly reputed journals and international conferences.

Bal S. Virdee is Director of the Center for Communications Technology in the School of Computing and Digital Media at London Metropolitan University. Prior to becoming an academic he has worked in industry for various companies including Philips, as an R&D Engineer, and at Teledyne Defense & Space as a Future Products Developer in RF/microwave communications systems. He has also taught at several academic institutions. Bal is currently a Senior Professor of Communications Technology. He serves on the Editorial Board of several international journals and has published numerous research papers. His research, in collaboration with industry, is in microwave, mm-wave & Thz wireless systems encompassing the latest cellular and satellite technologies. He is Chair and Executive Member of the IET's Technical and Professional Network Committee on RF and Microwave Technology. He is a Fellow of the IET and Senior Member of IEEE.

Richa Sharma has over 20 years’ experience in IT Industry and Academia, first as Network Engineer for Cisco Systems and then as Lecturer at Birmingham City University and London Metropolitan University. She gained a master’s degree from Aston University. She is a qualified Cisco Certified Academy Instructor for CCNA and CCNP courses. She is currently pursuing a PhD in wireless technology related to adaptive IoT networks.

Taha A. Elwi received his B.Sc. in Electrical Engineering Department (2003) (Highest Graduation Award), Postgraduate M.Sc. in Laser and Optoelectronics Engineering Department (2005) (Highest Graduation Award) from Nahrain University Baghdad, Iraq. From April 2005 to August 2007, he was working with Huawei Technologies Company, Baghdad, Iraq. On January, 2008, he joined the University of Arkansas at Little Rock and he obtained his Ph.D. in December 2011 from the system engineering and science. His research areas include wearable and implantable antennas for biomedical wireless systems, smart antennas, WiFi deployment, electromagnetic wave scattering by complex objects, design, modeling and testing of metamaterial structures for microwave applications, design and analysis of microstrip antennas for mobile radio systems, precipitation effects on terrestrial and satellite frequency re-use communication systems, effects of the complex media on electromagnetic propagation and GPS. The nano-scale structures in the entire electromagnetic spectrum are a part of his research interest.

Lida Kouhalvandi, IEEE member & PhD (with honor), joined the Department of Electrical and Electronics Engineering at Dogus University as an assistant professor in October 2021. She received her PhD in Electronics Engineering in 2021 from the Istanbul Technical University, Istanbul, Turkey. She received her MSc in Electronics Engineering in 2015 from the Istanbul Technical University, Istanbul, Turkey, and her BSc in Electronics Engineering in 2011 from the Azad University of Tabriz, Tabriz, Iran. In recognition of her research, she received the Doctoral Fellowship at Department of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy from 2019 to 2020 and also she joined to Politecnico di Torino, Turin, Italy as a Research fellowship from February 2021 up to July 2021. Dr. Kouhalvandiˆas research interests as a radio frequency and analog engineer are power amplifier, antenna, analog designs, and implantable medical devices. She also has experience in computer-aided designs and optimization algorithms through machine learning. she received ’Best Paper Award’ from EExPolytech-2021: Electrical Engineering and Photonics conference in 2021. Additionally, her PhD thesis accepted for the presentation at PhD Forum of the 2021 IEEE/ACM Design Automation Conference (DAC 2021) in San Francisco, USA. From the 30th IEEE conference on signal processing and communications applications, she received another ’Best Paper Award’ in 2022. She received the 2022 Mojgan Daneshmand Grant from the IEEE Antennas and Propagation Society (AP-S), organized by the IEEE AP-S Young Professionals. Additionally, her PhD thesis was awarded by Istanbul Technical University as the 'Outstanding PhD Thesis' and also from Turkish Electronics Industrialists Association (TESID) as the 'Best Innovation and Creativity PhD Thesis' in 2022.

Nurhan Türker Tokan received her B.Sc. degree in Electronics and Communications Engineering from Kocaeli University in 2002 and her M.Sc. and Ph.D. degree in Communication Engineering from Yildiz Technical University (YTU), Istanbul, Turkey, in 2004 and 2009, respectively. From May 2003 to May 2009, she worked as a research assistant in the Electromagnetic Fields and Microwave Technique Section of the Electronics and Comm. Eng. Dept. of YTU, Istanbul, Turkey. Between May2 009 and April 2015, she worked as an assistant professor and between April 2015 and August 2021, she worked as an associate professor in the Electronics and Comm. Eng. Dept. of YTU. Since August 2020, she has been working as a professor at the same department. From October 2011 to October 2012, she was Postdoctoral researcher in the EEMCS Department of Delft University of Technology, Delft, Netherlands. From October 2012 to May 2013, she was a Postdoctoral Fellow supported by European Science Foundation at the Institute of Electronics and Telecommunications (IETR), University of Rennes1, Rennes, France. She is the author or coauthor of more than 50 papers published in peer-reviewed international journals and conference proceedings. Her current research interests are analysis and design of antennas with emphasis on dielectric lens antennas and wideband antennas, microwave circuits and intelligent systems.

Patrizia Livreri, PhD, is a Professor with the Department of Engineering, University of Palermo, and a Visiting Professor with the San Diego State University. She received her “Laurea degree” in Electronics Engineering with honors in 1986 and her Ph.D. in Electronics and Communications Engineering in 1992, both from the University of Palermo, Italy. From 1993 to 1994, she was a researcher at CNR. Since 1995, she has been serving as the scientific director for the “Microwave Instruments and Measurements Lab” of the Engineering Department at the University of Palermo. In 2020, she also joined the CNIT National Laboratory for Radar and Surveillance Systems RaSS in Pisa. Her research interests are in microwave and millimeter vacuum high power (TWT, Klystron) and solid-state power amplifiers for radar applications; high power microwave source (virtual cathode oscillator, magnetically insulated transmission line oscillator); microwave and optical antennas, radar, and microwave quantum radar. She is the principal investigator of the “Microwave Quantum Radar” project, funded by the Ministry of Defense in 2021. She is the supervisor of many funded projects and the author of more than 200 published papers.

Francisco Falcone received the degree in telecommunication engineering and the Ph.D. degree in communication engineering from the Universidad Pública de Navarra (UPNA), Spain, in 1999 and 2005, respectively. From February 1999 to April 2000, he was the Microwave Commissioning Engineer at Siemens-Italtel, deploying microwave access systems. From May 2000 to December 2008, he was a Radio Access Engineer at Telefónica Móviles, performing radio network planning and optimization tasks in mobile network deployment. In January 2009, as a co-founding member, he has been the Director of Tafco Metawireless, a spin-off company from UPNA, until May 2009. In parallel, he is an Assistant Lecturer with the Electrical and Electronic Engineering Department, UPNA, from February 2003 to May 2009. In June 2009, he becomes an Associate Professor with the EE Department, being the Department Head, from January 2012 to July 2018. From January 2018 to May 2018, he was a Visiting Professor with the Kuwait College of Science and Technology, Kuwait. He is also affiliated with the Institute for Smart Cities (ISC), UPNA, which hosts around 140 researchers. He is currently acting as the Head of the ICT Section. His research interests are related to computational electromagnetics applied to the analysis of complex electromagnetic scenarios, with a focus on the analysis, design, and implementation of heterogeneous wireless networks to enable context-aware environments. He has over 500 contributions in indexed international journals, book chapters, and conference contributions. He has been awarded the CST 2003 and CST 2005 Best Paper Award, the Ph.D. Award from the Colegio Oficial de Ingenieros de Telecomunicación (COIT), in 2006, the Doctoral Award UPNA, 2010, 1st Juan Gomez Peñalver Research Award from the Royal Academy of Engineering of Spain, in 2010, the XII Talgo Innovation Award 2012, the IEEE 2014 Best Paper Award, 2014, the ECSA-3 Best Paper Award, 2016, and the ECSA-4 Best Paper Award, 2017.

Ernesto Limiti is a full professor of Electronics in the Engineering Faculty of the University of Roma Tor Vergata since 2002, after being research and teaching assistant (since 1991) and associate professor (since 1998) in the same University. Ernesto Limiti represents University of Roma Tor Vergata in the governing body of the MECSA (Microwave Engineering Center for Space Applications), an inter-universitary center among several Italian Universities. He has been elected to represent the Industrial Engineering sector in the Academic Senate of the University for the period 2007-2010 and 2010-2013. Ernesto Limiti is actually the president of the Consortium “Advanced research and Engineering for Space”, ARES, formed between the University and two companies. Further, he is actually the president of the Laurea and Laurea Magistrale degrees in Electronic Engineering of the University of Roma Tor Vergata. The research activity of Ernesto Limiti is focused on three main lines, all of them belonging to the microwave and millimetre-wave electronics research area. The first one is related to characterisation and modelling for active and passive microwave and millimetre-wave devices. Regarding active devices, the research line is oriented to the small-signal, noise and large signal modelling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical MMIC passive components (MIM capacitors) and to waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterisation and the subsequent modelling, and equivalent-circuit modelling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, InP MESFET/HEMT devices. The second line is related to design methodologies and characterisation methods for low noise circuits. The main focus is on cryogenic amplifiers and devices. Collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programmes (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed, together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations within international conferences. Ernesto Limiti acts as a referee of international journals of the microwave and millimetre wave electronics sector and is in the steering committee of international conferences and workshops. He is actively involved in research activities with many research groups, both European and Italian, and he is in tight collaborations with high-tech italian (Selex - SI, Thales Alenia Space, Rheinmetall, Elettronica S.p.A., Space Engineering …) and foreign (OMMIC, Siemens, UMS, …) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6 and FP7 …) projects. Regarding teaching activities, Ernesto Limiti teaches, over his istitutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, “Elettronica per lo Spazio” within the Master Course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare. He is a member of the committee of the PhD program in Telecommunications and Microelectronics at the University of Roma Tor Vergata, tutoring an average of four PhD candidates per year.